

**Linking memory and language:
Evidence for a serial-order learning impairment in dyslexia**

Louisa Bogaerts¹, Arnaud Szmalec², Wibke M. Hachmann³, Mike P.A. Page⁴, & Wouter
Duyck¹

¹Ghent University, Ghent, Belgium

²Université Catholique de Louvain, Louvain-La-Neuve, Belgium

³University of Trento, Rovereto, Italy

⁴University of Hertfordshire, Hatfield, UK

Correspondence Address:

Louisa Bogaerts

Ghent University, Department of Experimental Psychology

Henri Dunantlaan 2

B-9000 Ghent (Belgium)

E-mail: louisa.bogaerts@UGent.be

Tel.: +32-(0)9-264.64.39

Abstract

The present study investigated long-term serial-order learning impairments, operationalized as reduced Hebb repetition learning (HRL), in people with dyslexia. In a first multi-session experiment, we investigated both the persistence of a serial-order learning impairment as well as the long-term retention of serial-order representations, both in a group of Dutch-speaking adults with developmental dyslexia and in a matched control group. In a second experiment, we relied on the assumption that HRL mimics naturalistic word-form acquisition and we investigated the lexicalization of novel word-forms acquired through HRL. First, our results demonstrate that adults with dyslexia are fundamentally impaired in the long-term acquisition of serial-order information. Second, dyslexic and control participants show comparable retention of the long-term serial-order representations in memory over a period of one month. Third, the data suggest weaker lexicalization of newly acquired word-forms in the dyslexic group. We discuss the integration of these findings into current theoretical views of dyslexia.

Keywords: dyslexia; memory; language acquisition; serial-order learning; retention

Introduction

Dyslexia

Developmental dyslexia is commonly defined as a learning disorder characterized by persistent difficulties with reading and/or spelling despite adequate intelligence, education and sensory functions (World Health Organization, 2008; Lyon, Shaywitz, & Shaywitz, 2003). Although the above definition focuses on problems with reading and spelling, the literature on dyslexia reveals a strikingly broad scope of associated nonlinguistic dysfunctions. Examples include impaired short-term memory (e.g., Martinez Perez, Majerus, Mahot & Poncelet, 2012a), working memory (e.g., Gathercole, Alloway, Willis, & Adams, 2006; Smith-Spark & Fisk, 2007), implicit (sequence) learning (e.g., Lum, Ullman, & Conti-Ramsden, 2013; Pavlidou, Kelly, & Williams, 2010; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), motor functions (e.g., Nicolson, Fawcett, & Dean, 2001) and sensory functioning (e.g., Stein, 2001, but see also Goswami, 2015).

The underpinnings of dyslexia remain a source of controversy. The influential phonological theory (Stanovich, 1988; Snowling, 2000) postulates that an impairment in the representation and processing of phonological information is the core underlying deficit in dyslexia. However, while phonological impairments are indeed found in a clear majority of the studies (Melby-Lervag, Lyster, & Hulme, 2012; Ramus & Ahissar, 2012; Ziegler & Goswami, 2005), the presumption of an etiological and causal role for these phonological problems in relation to reading is not without its critics (Blomert & Willems, 2010; Castles & Coltheart, 2004). Most importantly, there is evidence for a double dissociation between dyslexia and phonological deficits: some individuals with

severe reading disability do not show a phonological impairment, while some children with an apparent phonological deficit nevertheless do achieve fluency in (word) reading (Paulesu et al., 2001; Wimmer, Mayringer, & Landerl, 2000). Moreover, it is unclear how some of the nonlinguistic impairments often associated with dyslexia (e.g., implicit learning or motor deficits) may be accounted for by phonological deficits. Perhaps as a result, diverse alternative theoretical accounts of dyslexia have been proposed (e.g., the automaticity/cerebellar deficit hypothesis, Nicolson & Fawcett, 1990; the anchoring-deficit hypothesis, Ahissar, 2007; the magnocellular theory, Stein, 2001) but a unifying framework that addresses the diversity of associated dysfunctions is still lacking (Pennington, 2006; Ramus et al., 2003). A recently introduced integrative hypothesis proposes that several of the associated dysfunctions observed in dyslexia arise from a deficit in memory for serial-order information (i.e., the order in which items are presented within a sequence; Szmalec, Loncke, Page, & Duyck, 2011). The present study builds on this novel hypothesis, which is explained in more detail later.

Serial-order memory and language learning

It is well known that both the immediate processing and the long-term learning of sequential information have relevance to language skills (Conway & Christiansen, 2001). First, there is the observation of a clear association between verbal immediate serial recall performance and the learning of novel phonological word-forms (Baddeley, Gathercole, & Papagno, 1998; Gathercole, Service, Hitch, Adams, & Martin, 1999; Gupta, 2003). At the theoretical level, models of short-term memory suggest that the encoding of item identity on the one hand, and serial order processing on the other hand, are distinct and dissociable functions (e.g., Burgess & Hitch, 1999, 2006; Gupta, 2003, 2008; Page &

Norris, 2009). These models contend that verbal item-information is stored via temporary activation of long-term phonological and lexico-semantic representations, with a strength depending primarily on the quality of these long-term traces (see also Majerus & D'Argembeau, 2011). In contrast, the encoding of serial order occurs via a system that operates on items, over-and-above those processes used in their individual recognition. Several recent studies by Majerus and colleagues have highlighted the importance of the serial-order processing component of short-term memory (STM), in addition to memory for item identity, in relation to novel word-form learning (e.g., Leclercq & Majerus, 2010; Majerus, Poncelet, Greffe, & Van der Linden, 2006; Majerus & Bo ukebza, 2013) and literacy acquisition (Martinez Perez, Majerus, & Poncelet, 2012b).

Recently, Page and Norris (2008, 2009) explicitly related word learning to a memory framework by extending their computational model of verbal short-term memory (the primacy model, Page & Norris, 1998) to word-form learning. They proposed that the order-STM processes described above contribute to long-term learning of new phoneme sequences (and by extension novel lexical or orthographic representations) via a mechanism that is also seen operating in Hebb repetition learning (HRL). HRL refers to the observation that when a particular ordered sequence of stimuli is repeated several times over the course of an immediate serial recall task, people show gradually enhanced recall of that sequence —known as the *Hebb* sequence— relative to *filler* sequences in which stimuli appear in a random order (Hebb, 1961). In essence, HRL reflects how, through repeated presentation and recall, an ordered sequence of information in short-term memory gradually develops into a stable, long-term memory trace. In the framework of Page and Norris (2008, 2009), a new word-form is conceived

as a familiarized sequence of sublexical components, such as phonemes or syllables (see also Gupta, 2008, for a similar view). HRL of a syllable sequence like “*lo fo du*” is therefore assumed to be functionally equivalent to acquiring the novel word-form “LOFODU”, similar to the way in which children learn new words by picking up statistical regularities from the verbal input in their environment (e.g., Saffran et al., 1996). Experimental evidence for the hypothesis that HRL mimics naturalistic word-form acquisition was provided by Szmalec and colleagues (Szmalec, Duyck, Vandierendonck, Barberá-Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). In these experiments, that included only normal readers, participants typically had to recall nonsense sequences of nine visually presented consonant-vowel syllables (CVs), with each sequence grouped by short pauses into three three-CV groups (e.g., “*fi ke da – sa mo pu – vo ti zu*”). A Hebb sequence, presented every third trial, always contained the same three three-CV groups, in a random group-ordering. Participants showed clear HRL (i.e., improved recall of sequences whose groups repeated relative to filler sequences). After learning, auditory lexicalization tests showed that the three-CV groups that had been repeatedly presented and recalled, exhibited the properties expected of novel word-form entries in the mental lexicon. In summary, these studies suggest that HRL draws on the same memory processes responsible for representing and learning serial-order information in the service of language acquisition (i.e., novel word-form learning).

Dyslexia as a dis-order?

Drawing on the crucial role that serial order plays in language learning and processing, Szmalec et al. (2011) proposed a novel hypothesis relating to dyslexia, that we will call the “SOLID” (Serial-order Learning Impairment in Dyslexia) hypothesis. It

offers an integrative account that clarifies how the problems encountered by people with dyslexia, not only in reading but also in other (nonlinguistic) tasks, may originate from a common underlying impairment in memory for serial-order information. Szmalec et al. demonstrated that dyslexic adults show reduced HRL, not only in verbal but also in visuospatial stimulus modalities. These data support the idea that people with dyslexia experience difficulties with serial-order learning and that these difficulties extend beyond the verbal domain (cf. the early work of Corkin, 1974; but see also Gould and Glencross, 1990).

Memory for serial order is also involved in tasks that have been traditionally used in the domain of statistical learning and implicit learning (see Perruchet & Pacton, 2006, for discussion). For example, in the Serial Reaction Time (SRT) paradigm (Nissen & Bullemer, 1987), participants are presented with sequences of visual stimuli, each appearing in one of four locations on a screen. They are required to press a particular key corresponding to a given location, each time a visual stimulus appears in that location. The serial order in which locations are occupied by the visual stimuli is probabilistically determined, and this regularity is learned implicitly by participants, as revealed by faster key-press reaction times for repeated sequences of locations. Memory for order is thus critical for performance in this task and it seems that, at least partly, similar order-learning mechanisms underlie performance in the Hebb repetition task and the SRT tasks (Page et al., 2006). In line with the SOLID hypothesis, a majority of studies using the SRT paradigm have reported impaired implicit-sequence-learning abilities in individuals with dyslexia (see Lum et al., 2013 for a recent meta-analysis and Pavlidou et al., 2010, for converging evidence in artificial grammar learning).

One fundamental characteristic of most serial-order learning tasks is that they proceed over a relatively extended time period (Hedenius et al., 2013), tapping into the transfer between short and long-term memory. This characteristic is particularly important in the case of the Hebb paradigm. First, a sequence needs to be encoded and temporarily represented in short-term memory. Second, via repeated presentation and recall of the sequence, a long-term memory trace of the item- and order information in a given sequence is gradually established, as shown by increased recall accuracy over successive Hebb trials (for normal readers, learning in a traditional HRL task displays improvements of around 3-4% per repetition; Page & Norris, 2008). Third, with time, the long-term representations that develop throughout HRL become more robust and resistant to interference (i.e., they undergo memory consolidation). Previous studies in normal readers have shown measurable savings from earlier HRL in an unannounced test three months after learning (Page & Norris, 2008), supporting the claim that HRL is indeed long-term learning. In the case of verbal HRL, it is assumed that the learned sequence creates novel entries in the mental lexicon (Szmalec et al., 2009, 2012; see above). Szmalec et al. (2011) explicitly characterized their serial-order account as a ‘learning account’: the dyslexic disadvantage is assumed to exist at the stage of the long-term learning of serial-order information (rather than solely at the stage of short-term representation of this information, although data suggest such a short-term deficit too – see below). It is especially this type of learning that is assumed to be crucial for learning words from sequence regularities in the phonological (and orthographic, when learning to read) input from the environment. Note, however, that the study by Szmalec et al. (2011) focused exclusively on learning within a single session and only looked at learning with a

relatively narrow practice interval (using only ten Hebb repetition trials). This leaves open the question of how people with dyslexia perform with more intensive repetition learning, and whether group differences can be found also in how well the learned sequential material is retained in memory over longer periods of time. It is possible that the dyslexic disadvantage affects not only learning, but also long-term retention of sequential verbal material. These questions, regarding performance after the initial learning stage, are addressed by the current study. They are particularly relevant given that people with dyslexia typically show therapeutic resistance (Vaughn, Thompson, & Hickman, 2003) and problems with automatization (i.e., the process by which skills gradually become so fluent that they no longer need conscious control, e.g., Nicolson et al., 2001). One recent study, that was unusual inasmuch as it investigated implicit sequence learning including long practice, is that by Hedenius et al. (2013). They tested the SRT performance of children with dyslexia and matched controls, including a first session with a large amount of practice and a second session on the subsequent day; this allowed them to investigate overnight consolidation. They reported an impairment in initial implicit sequence learning for dyslexics, but even more pronounced group differences in learning after extended practice. No group difference in the overnight retention of the learned material was observed.

Drawing on the assumption that verbal HRL relies on the same memory mechanisms that serve lexical acquisition (Page & Norris, 2008, 2009), and on the recent demonstration of impaired HRL in dyslexia, an additional important question is how an order-learning deficit may account for the language problems that are central to dyslexia, in particular the low reading achievement. Several recent models of reading stress the

importance of the temporal alignment of the serial orthographic representations (i.e., letter position and identity) and phonological representations in reading acquisition (e.g., the SERIOL model, Whitney, 2001; the overlap model, Gomez, Ratcliff, & Perea, 2008). When encountering an as-yet-unknown orthographical word-form in an alphabetic language, a reader will typically use a decoding strategy through which s/he converts letters into the corresponding sounds¹, integrating a representation of the entire sequence of sounds into a single word-form (e.g., the dual route cascaded model, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Repeatedly processing the same sequence of letters will then gradually develop a lexical representation in the mental lexicon. The presence of such a representation allows more automatic and proficient processing of the (now known) letter string. In our view, the acquisition of novel orthographical and phonological word-forms strongly relies on memory for serial information, and as a result, a deficit in serial-order learning would lead to problematic word-form (or lexical) learning. In line with the lexical-quality hypothesis (Perfetti, 2007), Szmalec et al. (2011) argued that if the order of the sublexical constituents of a newly learned word is not optimally consolidated as a single lexical entry in long-term memory, its lexical representation will be impoverished.² This, in turn, could impair lexical access for that entry, disrupt normal procedures for mapping grapheme sequences to phoneme sequences

¹ Alphabetic orthographies differ in the consistency of their grapheme-to-phoneme correspondence, ranging from highly consistent or ‘transparent’ (e.g., Finnish, Spanish) to inconsistent or ‘opaque’ (e.g., English, French). In the current paper we tested speakers/readers of Dutch. The Dutch orthography is considered relatively transparent since grapheme-to-phoneme correspondences are fairly consistent, but there are notable exceptions (e.g., /t/ written as d at the end of some words). Additionally, the letters a, o, e, and u can indicate either long or short vowels, depending on their location in a syllable (Patel, Snowling, & de Jong, 2004; Ziegler et al., 2010).

² As noted previously (p. 5), the short-term processing and storage of the (sublexical) item information is sensitive to the quality of verbal long-term memory representations (e.g., Gupta, 2003, Majerus et al., 2008). Less well-defined or noisy representations of the items themselves might therefore also (independently) contribute to difficulties in lexical learning and reading (e.g., Martinez-Perez, Majerus, & Poncelet, 2013).

(Whitney & Cornelissen, 2005), and hence affect reading accuracy and fluency (Kuperman & Van Dyke, 2011; Perfetti, 2007). However, to our knowledge, no published research has tested whether the impaired long-term learning of verbal serial information for people with dyslexia is indeed associated with difficulties in acquiring novel lexical representations.

Current Study

The aim of the present study is threefold. First, we aim to investigate how resistant people with dyslexia are to serial-order learning: Is the Hebb learning impairment persistent (i.e., an ongoing capacity deficit) or can people with dyslexia, with more practice (in this case, more Hebb repetitions), reach the same serial-order learning performance level as control participants, implying that learning is just slower in dyslexia? Second, we aim to distinguish between learning and retention deficits: Are people with dyslexia only impaired in serial-order learning or is the long-term retention of the acquired order representations also affected (i.e., there is faster degradation over time)? Third, we aim to make the link between memory and language impairments explicit, by investigating whether poor verbal serial-order learning in dyslexia also leads to poor lexicalization of the learned verbal sequences. We will, henceforth, refer to these three research goals as *resistance*, *retention* and *lexicalization*.

The present study reports two experiments. Experiment 1 covers the first two goals. It extends the previous examination of HRL in adults with dyslexia (Szmalec et al., 2011) by including not only an initial Hebb-learning session with a much larger number of Hebb repetitions (up to 20 in the current study vs. 12 in Szmalec et al., 2012) but also re-learning on the subsequent day and one month after initial learning. This allows us to

estimate the retention of the learned Hebb sequences over time. Because the acquisition of natural language unfolds over time, HRL (as its hypothesized laboratory analogue) should therefore be tested longitudinally. In the control group, we expected to observe the well-replicated HRL effect, as well as significant retention of the Hebb materials across the re-learning sessions (Page & Norris, 2008). For people with dyslexia, we predicted not just slower Hebb learning but also a persistent impairment in HRL, despite the opportunity (in terms of number of repetitions) for substantial overlearning (i.e., we predicted *resistance*). We anticipated that people with dyslexia would be likely to benefit less from initial learning when asked to relearn the same Hebb sequences across sessions (i.e., we predicted lower *retention*). This prediction is notwithstanding the fact that the only published study on overnight retention of sequential information in dyslexia (Hedenius et al., 2013) did not find such a group difference. Experiment 2 retested long-term retention of serial-order information, investigated in Experiment 1, now also controlling for possible task learning or strategic effects by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list. It also addressed our third goal, which was to investigate the lexicalization of word-forms acquired through HRL and, for the first time, test whether, as we tentatively predicted, such lexicalization is worse for people with dyslexia.

EXPERIMENT 1

Method

Participants

Twenty-five adults with dyslexia and 25 matched controls (participants were

matched as groups) were paid for participation. All were native Dutch speakers enrolled in higher education. All participants with dyslexia had a history of dyslexia that dated back to childhood and had obtained an official diagnostic certificate of developmental dyslexia through a government-approved diagnostic center (vzw Cursief, Ghent, Belgium). Criteria for diagnosis implied a score below the 10th percentile on the Gletschr (De Pessemier & Andries, 2009), a validated instrument for assessing reading and writing abilities in Dutch. Subjects with reported comorbidities were not included. For further validation, we administered the Eén Minuut Test (Brus & Voeten, 1979), the standard Dutch word reading test, and the Klepel (Van den Bos, Spelberg, Scheepsmma, & de Vries, 1994), the standard nonword reading test. The Eén Minuut Test consists of 116 words of increasing difficulty. The participant has to read aloud as many words as possible in one minute. Similarly, the Klepel contains 116 nonwords that follow the Dutch grapheme-phoneme correspondence rules. The participant has two minutes to read aloud as many nonwords as possible.

The two groups were matched on IQ using the fluid intelligence subscales (i.e., symbol learning, logical reasoning, secret codes, block patterns, delayed auditory memory, and delayed symbol learning) from the Flemish version of the Kaufman Adolescent and Adult Intelligence Test (KAIT; Dekker, Dekker, & Mulder, 2004; see Callens, Tops, & Brysbaert, 2012).

The order of the KAIT, EMT and Klepel was counterbalanced. Reading tests and KAIT were administered only to participants for whom these data were not available from a prior study (Callens et al., 2012). Two control participants were excluded from analysis: one had previously participated in a similar Hebb study and the other reported

problems learning foreign languages. Table 1 shows that individuals with dyslexia and controls only differed on the reading tests.

Materials and Procedure

Hebb learning. The Hebb learning task was identical in all three sessions. In a Hebb learning block, sequences of nine consonant-vowel syllables (CVs) were presented visually for immediate serial recall. One particular sequence, the Hebb sequence, was “repeated” on every third trial (in a manner similar to Szmalec et al., 2011, 2012, and as described below). On the other trials, the filler trials, the order of the syllables was randomized. To ensure that the Hebb task was sensitive only to learning order information and not to learning the individual items, all sequences (i.e., repeated and non-repeated) within a Hebb learning block were permutations of the same set of nine syllables. Each participant completed two Hebb learning blocks and thus learned two different Hebb sequences, yielding 6 different (three-syllable) pseudowords. HRL was terminated when the participant recalled two subsequent Hebb trials correctly, with a maximum of 20 Hebb repetitions. The Hebb sequences consisted of three three-syllable groupings that were unique neighbors of existing Dutch words (see Table 2). This allowed us to investigate lexicalization of the Hebb sequences through lexical competition. However, due to technical problems, the lexicalization test could not be performed in Experiment 1 and was therefore postponed until Experiment 2. The order of the CVs within the three-syllable subgroups was kept constant, but not the order of the entire nine-syllable Hebb sequence. For example, a legal Hebb “repetition” of the sequence *la-va-bu-sa-fa-ra-re-si-di* could be *re-si-di-la-va-bu-sa-fa-ra*. This procedure is

in a sense more conservative than standard HRL (as the repetitions are not full repetitions) while it resembles more closely the task faced by a word-form learner, who is confronted over and over again with the same lexical elements, in different orders. Hence, the procedure allows participants to extract the three-syllable groupings from the nine-syllable sequences (i.e., statistical learning). In addition, a blank screen was presented for 500ms in between the three-syllable groupings (*la-va-bu* [blank] *sa-fa-ra* [blank] *re-si-di*) to facilitate extraction of the subgroups that overlap with the Dutch base-words. The filler sequences were constructed from the same CVs as the Hebb sequences, but the CVs were presented in a different random order on each trial. Figure 1 shows an example of a possible set of trials. On each trial, the nine CVs were presented for 500ms with an inter-stimulus interval of 0ms within the three-syllable groupings and 500ms between group boundaries. Immediately after presentation, a recall screen showed the nine CVs, arranged randomly in a “noisy” circle around a central question mark. Participants were instructed to recall the order of the CVs by clicking the items in the order of presentation and to click the question mark for omitted CVs. Note that this procedure allows participants to repeat a CV. However, it was not possible to recall an item that was not in the stimulus list. After the participant had clicked nine responses, he or she was able to advance to the next trial by pressing the spacebar.

In each of Sessions 2 and 3 the two Hebb sequences that the subject had learned during Session 1 were relearned. The order of the two Hebb sequences was counterbalanced.

Results

Hebb learning

A CV was scored as correct if it was recalled in the correct position in the nine-syllable sequence. HRL in Session 1 was measured by taking the standardized gradient of the regression line through the points representing the performance on successive Hebb repetitions and comparing it with the corresponding gradient for the intermediate fillers, for each individual participant (see Page, Cumming, Norris, Hitch, & McNeil, 2006). The standardized gradient serves as a measure of the strength of learning (i.e., the steepness of the learning curve over repetitions), independent of the exact number of repetitions (as the number of repetitions was not the same for all participants)³. Mean gradient values (average of the two Hebb learning blocks) are presented in Table 3. The mean gradient values were entered into an analysis of variance (ANOVA) with Sequence type (filler vs. Hebb) and Group (control vs. dyslexic) as independent variables. The results are summarized in Table 4. Crucially, we found a significant interaction between Sequence type and Group, $F(1,46) = 4.73$, $\eta_p^2 = 0.09$, $p < .05$. Planned comparisons indicate a HRL effect in both groups, however, HRL was significantly stronger for controls. Additionally, we looked at the number of repetitions required to reach the criterion of two subsequent correctly recalled Hebb trials. The number of repetitions was entered into an ANOVA with Session (session 1 vs. session 2 vs. session 3) and Group (control vs. dyslexic) as independent variables. We found a significant effect of Group, indicating that participants with dyslexia require more repetitions to reach the HRL criterion. Planned comparisons on this measure show that the effect of Group is significant in all

³ As outlined by Staels and Van den Broeck (2014) a concern with the gradient measure of HRL is that the learning gradient (i.e., slope) tends to negatively correlate with initial performance (i.e., intercept). Note however that if anything such a negative correlation would work against our hypothesis as initial performance for the dyslexic group is expected to be either lower or comparable to initial performance in the control group.

three sessions. It is important to note that not all participants reached the criterion within the foreseen maximum of 20 repetitions and that the dyslexic participants reached the criterion less often than the control group. In Session 1, 48.0% of the participants with dyslexia failed to reach the recall criterion for at least one of the two repeating lists, despite considerable opportunity for learning, whereas controls had a failure rate of only 17.4%. In Session 2, this learning resistance was 36.0% and 0.0%, and in Session 3 24.0% vs. 0.0%, respectively.

Performance on the filler sequences (i.e., baseline recall performance, for the non-repeated items, measuring STM for order but not long-term serial-order learning) did differ significantly between groups, with the dyslexic group showing lower average performance (35.7%) than the control group (42.2%), $F(1,46) = 5.46$, $\eta_p^2 = 0.11$, $p < .05$. To test whether the Hebb learning impairment in dyslexia is robust against those baseline filler differences, we compared the Hebb learning effect (i.e., gradient Hebb – gradient filler) as well as the number of repetitions required to reach criterion between the two groups (control vs. dyslexic) in an analysis of covariance (ANCOVA), including average filler performance as a covariate. Because we had precise theoretically grounded predictions regarding the direction of this effect, one-tailed p-values are reported. The group difference in HRL was replicated using both the gradient measure, $F(1,45) = 3.31$, $\eta_p^2 = 0.07$, $p < .05$, and the number-of-repetitions measure, $F(1,45) = 9.76$, $\eta_p^2 = .18$; $p < .01$), when filler performance was covaried out. This suggests that weaker HRL for people with dyslexia is not, or not only, due to worse baseline (short-term) memory capacity.

Retention

In order to estimate retention of HRL, independently of initial learning differences, we subtracted performance on the first Hebb trial in Session 2 from performance on the final Hebb trial in Session 1 for each participant. This difference was divided by the final performance of Session 1 to obtain a proportional measure of saving. The same was done for savings between Session 2 and Session 3. Figure 2a depicts the mean proportion of correctly recalled Hebb items on the different points in time (end performance Session 1 vs. start performance Session 2; end performance Session 2 vs. start performance Session 3) for dyslexic participants and controls. The graph clearly shows learning differences, but the lines for both groups that reflect saving are almost perfectly parallel. Planned comparisons on these two relative retention measures show no significant effects of group, both $F_s < 1$, indicating comparable retention for both groups, both 24h and one month after HRL (see Table 4).

One could argue that whereas the two groups show parallel savings (see Figure 2a), the individuals with dyslexia are losing a greater proportion of what they initially attained. A second analysis therefore examined the degree of retention when fully equating the degree of acquisition across the two groups by including only those participants who reached the criterion of two subsequent correctly recalled Hebb trials in the first session ($n_{\text{control}} = 20$, $n_{\text{dyslexic}} = 12$). Figure 2b shows the retention graphs for these subgroups. Planned comparisons indicate again comparable retention for the two groups, both 24h and one month after HRL, $F_s < 1$, which strengthens our conclusion of comparable retention for both groups.

Discussion

The aim of Experiment 1 was to examine HRL impairment in dyslexic adults including not only an initial learning session with a large number of Hebb repetitions, but also further learning on the subsequent day and one month after initial learning. This allowed us to investigate how resistant people with dyslexia are to long-term serial-order learning, and also to estimate the retention of the learned Hebb sequences over time.

First, the results of Experiment 1 show that the impairment in serial-order learning is genuine in the sense that people with dyslexia are resistant to Hebb learning of syllable sequences. Our participants with dyslexia needed substantially more repetitions to develop an effective long-term representation of the Hebb sequences and several people with dyslexia even failed fully to develop this long-term serial-order representation despite the large number of repetitions. Clear group differences were observed, not only for HRL in the first session, but also for further practice on day two and after one month. In contrast to Szmalec et al. (2011), the two groups of the current study did differ in their filler performance, suggesting a group difference in short-term memory for order information. However, when we controlled for this baseline difference by analyzing the results with an ANCOVA, controlling for average filler performance, the finding of impaired serial-order *learning* in dyslexia remained reliable on both measures.

Secondly, dyslexic and control participants showed comparable retention when relearning the Hebb sequences both 24h and one month after initial learning. This suggests that, although serial-order learning is slower and weaker, the representations that are eventually learned seem to stand the test of time rather well, at least for a retention period of one month.

EXPERIMENT 2

In Experiment 2 we sought to replicate the findings relating to impaired long-term retention of serial-order information observed in Experiment 1, now also controlling for possible task-specific or strategic effects by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list one month after initial learning. Furthermore, we assessed lexical engagement of word-forms acquired through HRL in people with dyslexia. With this aim, participants again learned Hebb sequences (e.g., la-va-bu-sa-fa-ra-re-si-di), containing lexical competitors (e.g., lavabu, safara, residu) of existing Dutch base-words (e.g., lavabo [kitchen sink], safari [safari], residu [residue]). Inherent to the use of the lexical competition approach is the requirement that Hebb sequences closely resemble known words represented in the mental lexicon. Importantly, the earlier studies using this lexical-competitor approach (Szmalec et al., 2012) have demonstrated that this procedure yields Hebb learning curves (for normal readers) comparable to standard verbal Hebb learning curves (Szmalec et al., 2009, 2011, 2012), suggesting that the learning of syllable sequences derived from existing words does not seem to rely on strong support from these words. This might be due to the fact that the Hebb procedure exposes the participant to individual syllables, presented one by one, while the gradual and implicit grouping of those syllables into pseudoword-forms is only the outcome of the Hebb-learning process. Also note that impaired Hebb learning by dyslexic participants has been demonstrated before with Hebb learning of syllable sequences that did not overlap with existing words (Szmalec et al., 2011).

We tested for lexical engagement of the acquired representations immediately and

again one month after HRL. Lexical engagement refers to the interaction of a novel word-form with existing entries in the mental lexicon (Gaskell & Dumay, 2003). The current study assesses the lexical engagement of the new phonological representations using a pause detection (PD) task on the overlapping Dutch base-words (Gaskell & Dumay, 2003; see also Szmalec et al., 2012). In a PD task, participants detect an artificially embedded pause in connected speech. Mattys and Clark (2002) demonstrated that the speed at which this artificial pause can be detected, depends on the overall amount of lexical activity caused by the speech preceding this pause. For example, words with a late uniqueness point (e.g., blackberry) that have a pause inserted near the end of the word (blackb_erry), will, during processing of the onset syllables, activate several lexical representations (e.g., blackbox, blackbird, blackboard, etc.). The activation of multiple lexical candidates consumes processing resources that could otherwise be allocated to the detection of the pause. Therefore, the PD time is a function of the number of phonological neighbors (or, by extension, lexical competitors) of the target word, which makes the task a good test of the lexicalization of newly acquired neighbors (Mattys & Clark, 2002; Szmalec et al., 2012).

In line with the results of Experiment 1, we anticipated comparable *retention* of the Hebb materials for both groups. Regarding the test of *lexicalization*, we predicted that the control group should show slower PD times on the existing Dutch base-words, neighbors of the newly created lexical entries, compared with a set of matched control words; this would indicate lexical competition from representations of the Hebb (sub)sequences. Knowing that lexical consolidation of Hebb sequences requires time (Szmalec et al., 2012), we particularly expected lexical engagement effects in Session 2.

Finally, we predicted reduced lexical competition from the Hebb sequences for the dyslexic group.

Method

Participants

Eighteen adults with dyslexia and 18 matched controls were paid for participation. Criteria for inclusion were identical to Experiment 1. We administered literacy with the Eén Minuut Test and the Klepel. The two groups were again matched on IQ using a short-form IQ measure (Turner, 1997), including the subscales Similarities, Comprehension, Block design and Picture completion from the Wechsler Adult Intelligence Scale (3rd ed.; Wechsler, 1998). One dyslexic participant failed to complete Session 2. Table 1 shows that for this sample too, individuals with dyslexia and controls only differed on the reading tests.

Materials and Procedure

Hebb learning. The materials in the Hebb task were identical to those in Experiment 1. The procedure was almost identical; the only difference was that in Session 1 there was an imposed minimum of 18 Hebb repetitions (i.e., 54 trials in total) that all participants had to complete, independent of their performance. We opted for this fixed minimum in order to boost HRL for the dyslexic group, but keeping the amount of exposure comparable between the two groups in the light of the subsequent lexicalization test. The maximum number of Hebb repetitions was 24 (i.e., 72 trials). In other words, each participant received between 18 and 24 repetitions of the Hebb sequence.

In Session 2, every participant was presented with one old (i.e., previously learned) and one new Hebb sequence. The order of the new and old sequence was counterbalanced and the old Hebb sequences were chosen so that half of the participants relearned the first Hebb sequence from Session1 whereas the other half relearned the second Hebb sequence from Session1. Small changes were applied to the procedure of the Hebb learning task in Session 2 to disrupt, as far as possible, the use of an explicit learning strategy: the first five trials were filler sequences and the Hebb sequence was repeated every fourth trial instead of every third trial. Additionally, the pauses between the three three-syllable subgroups were omitted and the presentation rate of the individual CV's was extended to 1000ms. The minimum number of Hebb repetitions in Session 2 was 12 and the maximum 18.

Pause detection. In the PD task, identical to the task used by Szmalec et al. (2012), 50 words were randomly presented once with, and once without, an embedded 150ms pause. Twenty-five words had a CVCVCV structure: the base-words, the control words and filler words. The critical materials were 18 trisyllabic base-words, that is, the lexical competitors of the 18 nonword Hebb sequences. In order to maximize potential (cohort-based) interference effects of the newly learned lexical competitor, the base-words differed from the nonwords only in their final letter (i.e., there was a late uniqueness point) and only words that had no existing lexical neighbors in Dutch were chosen (see Table 2). The 18 base words had a mean frequency of 2.77 (occurrences per million, as per Duyck, Desmet, Verbeke & Brysbaert, 2004). Because two Hebb lists were learned, each containing three 3-syllable nonwords, each participant had 6 base-

words. The same words constituted the control condition for some participants, while serving as the lexical competition condition for others. Word frequencies of base- and control words were matched.

The words were presented through headphones (60 dB). The presentation time was 800ms (pause-absent) or 950ms (pause-present), with a 2500ms interstimulus interval (see Szmalec et al., 2012, for further stimulus details). Participants had to decide as accurately and quickly as possible whether a pause was present or not by pressing one of two buttons. In the pause-absent trials, RTs were measured from the same point at which the pause was inserted in the pause-present condition.

Results

Hebb learning

The scoring procedure was identical to the one used in Experiment 1: a CV was scored as correct if it was recalled in the correct position in the sequence. Mean gradient values (average of the two Hebb learning blocks in Session 1, the gradient was calculated on performance till the criterion of two subsequent correctly recalled Hebb trials was reached) were entered into an ANOVA with Sequence type (filler vs. Hebb) and Group (control vs. dyslexic) as independent variables (see Table 5 for a summary of the results). In line with the results of Experiment 1, a significant interaction was found between Sequence type and Group, $F(1,34) = 5.52$, $\eta_p^2 = 0.14$, $p < .05$. Additionally, we looked at the number of repetitions required to reach the criterion of two subsequent correctly recalled Hebb trials. Planned comparisons on this measure show a significant effect of Group in Session 1 as well as Session 2, indicating that participants with dyslexia show

reliably slower HRL. In Session 1 not all participants reached the criterion within the foreseen maximum of 24 repetitions, with a clear disadvantage for the dyslexic group: 61.1% of the participants with dyslexia failed to reach the recall criterion before or on repetition 24 (for at least one of the two repeating lists), controls had a failure rate of only 5.6%. For the old (i.e., to be relearned) Hebb list in Session 2, learning resistance was 27.8% for the dyslexic group versus 0.0% for the control group (maximum of 18 repetitions).

Performance on the fillers did differ significantly between groups. Again, the dyslexic group showed lower average performance (41.4%) than the control group (52.1%), $F(1,33) = 9.90$, $\eta_p^2 = 0.23$, $p < .005$. As for Experiment 1, we tested whether the group difference in Hebb learning is robust against the observed filler differences by including average filler performance as a covariate in an ANCOVA. The number of repetitions required to reach the criterion was, as expected, significantly higher for the dyslexic group, while for the gradient measure the group effect just failed to reach significance (respectively $F(1,32) = 6.02$, $\eta_p^2 = 0.16$, $p < .01$. and $F(1,33) = 2.40$, $\eta_p^2 = 0.07$, $p = .05$, p -values both one-tailed).

Retention

First, we compared initial performance (i.e., performance on the first Hebb trial) on the new versus the old Hebb sequences learned in Session 2. Savings are in this case reflected as better performance on the old compared with the new Hebb sequence. An ANOVA with Hebb List (new vs. old) and Group (control vs. dyslexic) as independent variables, and the initial performance on the Hebb sequence in Session 2 as the dependent

variable showed a main effect of group, with lower performance for the dyslexic group ($M(\text{new})_{\text{control}} = 77.2\%$, $SD = 27.9$, $M(\text{old})_{\text{control}} = 92.0\%$, $SD = 13.6$; $M(\text{new})_{\text{dyslexia}} = 56.9\%$, $SD = 30.7$; $M(\text{old})_{\text{dyslexia}} = 60.1\%$, $SD = 24.2$). We observed a marginally significant effect of Hebb List, with on average higher performance for the old Hebb sequence. Crucially, however, we did not find a significant interaction between Hebb List and Group (see Table 5). Second, we looked at the difference of the number of repetitions needed for reaching criterion for the new vs. old sequence. A positive number (i.e., more repetitions for the new Hebb sequence compared to the old) indicates the benefit of re-learning, in other words, savings. No group difference was found whatsoever, $F < 1$ ($M_{\text{control}} = 2.66$, $SD = 5.42$; $M_{\text{dyslexia}} = 3.35$ $SD = 5.11$). The results on both measures indicate that retention did not differ for both groups over the period of one month.

Lexicalization

Mean RTs for the different conditions of the PD task are presented in Table 6. The lexical competition effect (i.e., RTs for base-words minus RTs for control words) is depicted in Figure 3. RTs were averaged across pause-present and pause-absent trials (cf. Dumay & Gaskell, 2007). RTs under 100ms and outliers (± 2.5 SDs) were removed (2.6% of data). Because only the difference between the base-words and control words is of theoretical interest, and we expected the difference to arise only in Session 2, t-tests are reported as a measure of lexical engagement within each session, and for both groups separately. In the control group, we observed evidence for lexical engagement of the Hebb sequences in Session 2, $t(16) = 2.14$, $d = 1.7$, $p < .05$; but not in Session 1, $t(16) = 0.44$, $p = .66$. In the group with dyslexia, there was no reliable evidence for lexical

engagement in either of the two sessions, Session 2, $t(15) = 0.68$, $p = .51$; Session 1, $t(15) = 0.001$, $p = .99$. It should be noted that even in Session 2, where we find, for control participants, the reliable lexical competition from newly learned Hebb sequences that we expected based on prior research, the interaction of this competition effect with Group (control/dyslexia) did not reach significance, $F(1,31) = 1.34$, $p = .26$. Given the nature of the competition effect, which is itself difficult to observe, the statistical power available to detect the interaction term is necessarily limited here. For this reason, the lack of a competition effect in either session for the dyslexic group must be seen as suggestive rather than definitive.

Accuracy on the PD task did not differ between the two groups ($M_{\text{control}} = 83.6\%$, $M_{\text{dyslexia}} = 81.8\%$), $F(1,31) = 2.00$, $p = .16$. No significant accuracy differences between the base and control words were observed, $F < 1$.

Discussion

The first aim of Experiment 2 was to examine further the long-term retention of serial-order information in adults with dyslexia and normal reading controls by contrasting the relearning of the previously learned Hebb list with the learning of a new Hebb list. The second aim was to assess the lexicalization of Hebb sequences in people with dyslexia.

First, the finding of impaired Hebb learning, demonstrated in Experiment 1, was replicated. Clear group differences could be observed on the gradient measure of Hebb learning. When looking at the number of repetitions, we observed that people with dyslexia needed almost twice as many Hebb repetitions to reach the learning criterion

(i.e., two successive correctly recalled Hebb trials) in all of the learning sessions. Second, we measured retention by comparing the initial performance on a new and an old Hebb list one month after HRL and by looking at the difference in number of repetitions needed to reach criterion on the new vs. the old list. We did not observe a group difference on either measure of retention. Third, lexicalization of Hebb sequences appeared to be less robust for dyslexic participants, though this conclusion needs to be qualified by the absence of an interaction moderating the size of the lexical competition across subject-groups. For the control group, the newly learned sequences of syllables (e.g., *la-va-bu*, *sa-fa-ra*, *re-si-di*) did not engage in lexical competition immediately after learning, but they did engage in lexical competition with known base-words (e.g., *lavabo*, *safari*, *residu*) after one month. This is consistent with previous work in normal reading adults (Szmalec et al., 2012), though the extension to a retention period of one month is novel. In the group with dyslexia however, lexicalization of the Hebb materials did still not occur after 1 month.

4. General discussion

The present study investigated long-term serial-order learning in dyslexia. We focused on extended learning beyond a short, single (Hebb) serial-order learning session, on the long-term retention of serial-order information in memory, and on the relationship between HRL and lexicalization in a dyslexic population. Overall, our results demonstrate that people with dyslexia are fundamentally impaired in the acquisition of serial-order information. More specifically, dyslexic participants needed more repetitions to develop long-term representations of the phonological Hebb sequences. Moreover,

even following more extensive repetition, a substantial number of participants with dyslexia failed to transfer the syllable sequences to long-term serial-order memory. Second, our findings suggest that the difficulty with serial order is indeed related to the initial serial-order acquisition phase rather than to the long-term retention of an acquired serial-order representation. Finally, people with dyslexia seemed to show less robust lexicalization of the newly acquired word-forms, although this effect was statistically less strong. Whereas the newly learned sequences of syllables (e.g., la-va-bu, sa-fa-ra, re-si-di) resulted in lexical competition with known base-words (e.g., lavabo, safari, residu) for normal readers, this lexicalization of Hebb sequences could not be observed in the group with dyslexia.

Natural language is sequential in nature. Typically, a limited number of phonemes or graphemes form different words, depending on their order, and these words in turn are sequentially aligned to form sentences. Long-term acquisition of serial-order information is therefore a critical component for extracting regularities from the phonological (and, by extension, orthographic) input which constitutes a given linguistic environment (see Aslin & Newport, 2012) and for learning new word-forms (Page & Norris, 2008, 2009; Szmalec et al., 2009, 2012). This rationale has been the basis of the Serial-Order Learning Impairment in Dyslexia (SOLID) hypothesis; an integrative account that proposes that both the linguistic and nonlinguistic dysfunctions in dyslexia could reflect a central deficit in serial-order learning. Previous work (Szmalec et al., 2011) indeed reported that adults with dyslexia show reduced HRL, across verbal and visuospatial modalities.

The current study extends the earlier findings of Szmalec et al. (2011) showing that people with dyslexia are fundamentally impaired in the *long-term acquisition* of verbal serial-order information, even following a substantially increased amount practice (i.e., a high number of Hebb repetitions). The finding that dyslexia appears to be associated with a fundamental serial-order *learning* deficit, more than a *retention* deficit, converges with recently reported data showing comparable overnight retention by dyslexic children in the context of the Serial Reaction Time (SRT) task (Hedenius, 2013). A learning, rather than a retention, deficit in dyslexia has also been shown in paired-associate word learning (e.g., Otto, 1961; Messbauer & deJong, 2003).

Our findings point towards a possible theoretical link between impaired Hebb learning and impaired language learning. Within our view, serial-order learning underlies new word-form acquisition. The observation that lexicalization of Hebb sequences was reliable for the control group, but not so for the group with dyslexia, suggests that problems with serial-order learning may be seen as a symptom of dyslexia that leads to impaired lexical representations (we acknowledge again, though, the lack of a reliable interaction here and, therefore, the need to strengthen this statistical claim in future work). This account converges with the reported difficulties of pseudoword learning in dyslexic children (e.g., Otto, 1961; Mayringer & Wimmer, 2000; Messbauer & deJong, 2003) and adults (Di Betta & Romani, 2006). Poor lexical quality, in turn, affects reading and spelling performance (see Perfetti, 2007). A serial-order account of dyslexia can therefore go some way to explaining the problems with reading and spelling characteristic of dyslexia. Interestingly, poor verbal HRL and impaired learning of motor sequences (in contrast to unimpaired performance on non-sequential procedural motor

learning) has also been demonstrated in children with a Specific Language Impairment (SLI), diagnosed when oral language lags behind (Hsu & Bishop, 2014). Recent research suggests that SLI and developmental dyslexia can best be treated as distinct, yet closely associated and potentially comorbid, language disorders (see Bishop & Snowling, 2004; Catts, Adlof, Hogan, & Ellis Weismer, 2005). On the one hand, oral language deficits are commonly reported in children with dyslexia (e.g., McArthur et al., 2000; Starck & Tallal, 1988). On the other hand, high rates of literacy problems are reported in children with SLI (e.g., Conti-Ramsden, Botting, Simkin, & Knox, 2001; Haynes & Naidoo, 1991; Tallal, Allard, Miller, & Curtiss, 1997), consistent with the link between lexicality and literacy explained above.

Importantly, the serial-order account (Szmalec et al., 2011) provides a useful perspective for understanding both the language impairments in dyslexia and the variety of nonlinguistic related dysfunctions that have been consistently reported throughout the years. Although not always explicitly recognized, the serial-order learning mechanisms that are the focus of this study, also constitute the basis of the experimental tasks that have been used to assess working memory (e.g., short-term serial recall or span task), implicit sequence learning (e.g., SRT task)⁴, artificial grammar learning, or sensorimotor (e.g., forced-choice paradigm) impairments in dyslexia. The current findings demonstrate verbal memory impairments in dyslexia, they are therefore not necessarily incompatible with the idea of a verbal processing deficit (see also Vellutino, 1977) and with the

⁴ Note that the SOLID hypothesis predicts difficulties for persons with dyslexia specifically in implicit learning tasks that require processing of serial-order information, and not in tasks that do not involve serial order. Evidence in line with this prediction was reported by Howard, Howard, Japikse, and Eden (2006). They tested adults with dyslexia on two different implicit learning tasks: a spatial contextual cuing task (in which the global configuration of a display cued the location of a search target), and a variant of the SRT task (in which sequential dependencies existed across non-adjacent elements). Crucially, only the latter task involved memory for serial-order. People with dyslexia showed impaired SRT sequence learning but unimpaired spatial context learning (see also Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011).

phonological theory of dyslexia (Stanovich, 1988; Snowling, 2000). However, previous demonstrations of sequence-learning impairments for people with dyslexia in non-linguistic tasks (e.g., visuospatial Hebb learning, Szmalec et al., 2011; Bogaerts, Szmalec, De Maeyer, Page, & Duyck, submitted; SRT task, Lum et al., 2013), seem to challenge the view that a selective verbal/phonological impairment underlies the full spectrum of symptoms associated with dyslexia. Moreover, serial-order processing seems to be largely a language-independent capacity (Burgess & Hitch, 1999, 2006; Gupta, 2003; see also Parmentier, 2014). We therefore suggest that the verbal-serial-order learning impairment in dyslexia observed in the current study likely reflects a problem with a core ability to represent serial-order information that cannot simply be accounted for by poor phonological representations. Moreover, we hypothesize that the evidence in support of a phonological impairment in dyslexia might, at least partly, be explained in terms of problematic serial-order representation and learning. First, tasks that measure phonological awareness (e.g., phoneme deletion, Spoonerisms) clearly involve serial-order processing, so that participants whose serial representations are compromised would necessarily display poor performance. Second, the dyslexic disadvantages in measures of short-term memory such as digit span and nonword repetition also imply a serial-order deficit, in temporary representation, if not in learning. Our present findings demonstrate how impaired serial-order learning could affect the formation of phonological/lexical verbal–serial representations, an observation that can also account for slow lexical retrieval and worse performance in rapid automatic naming (RAN) tasks reported for people with dyslexia. The serial-order hypothesis is, therefore, compatible

with the phonological deficits documented in the literature, and our lexicalization data do suggest a relation between serial-order impairments and wordform-learning impairments. The precise nature and causal structure of the relationship between reading and sequential learning (see Hari & Renvall, 2001; Hedenius et al., 2013) remains to be elucidated and, accordingly, we recently conducted a longitudinal study that addressed this issue (Bogaerts et al., submitted). Verbal and visual Hebb repetition learning performance and reading skills were assessed in 96 children (including children at risk of dyslexia) whom we followed from the first through to the second grade of primary school. We observed a positive association between individual order-learning capacities and (later) reading ability, as well as significantly weaker Hebb learning performance in early readers with poor reading skills, even at the onset of reading instruction. Hebb learning further explained a significant part of the variance in reading performance, above and beyond phonological awareness. This strengthens the claim of the SOLID hypothesis that poor HRL performance in dyslexia is probably not simply a consequence of degraded sublexical representations, but rather represents a genuine cognitive deficiency underlying dyslexia.

One point that deserves more attention is our use of visual (orthographic) representations for the syllables in the Hebb procedure. We opted for visual rather than auditory presentation of the CVs for two reasons: First, this allowed presenting the items simultaneously on the recall screen and therefore permitted a selective measure of serial-order performance uncontaminated by item memory. Second, the visual presentation of the Hebb competitors combined with an auditory PD task allows us to attribute lexical competition effects to abstract lexical representations, rather than just auditory traces in

episodic memory. Whereas we acknowledge the slight possibility that the dyslexic subjects had difficulty with the processing of the visually presented CVs, we argue that this is not likely to be the locus of the observed effects. First, only reading of individual CVs was required. Second, problems with phonological processing should arise both on filler and Hebb trials and therefore cannot explain a smaller HRE (i.e., the difference between the filler and Hebb trials). Third, earlier work (Szmalec et al., 2011) on Hebb learning in dyslexia showed that the Hebb learning impairment in the visual-verbal modality is not larger than in the auditory-verbal and spatial modalities.

The current study focuses on the *long-term* learning of serial-order information that, within Page and Norris's (2008, 2009) framework, is crucial when people learn words from sequence regularities in their linguistic environment. However, we do not exclude the possibility that the mere temporary processing of serial-order information is also affected in dyslexia (as put forward by Corkin, 1974; see also Martinez-Perez et al., 2012a; Martinez-Perez, Majerus, & Poncelet, 2013; Hachmann et al., 2014). Indeed, the group difference in filler performance found in the current study even suggest such a difference in immediate-recall performance. As we have mentioned already in our introduction, several recent studies have further highlighted the importance of the serial-order component of STM in relation to language learning and reading (e.g., Leclercq & Majerus, 2010; Martinez Perez et al., 2012b; Majerus & Boukebza, 2013). This suggests that both short-term memory for serial-order and the long-term Hebb learning of lists over multiple trials are strongly implicated in language processing and learning (see also Mosse & Jarrold, 2008). Our data show that when controlling for short-term memory differences, the finding of impaired serial-order learning in dyslexia remains reliable.

However, more research is needed to draw firm conclusions about the interrelation of the two memory systems and their relative importance in dyslexia.

Conclusion

In conclusion, the present article draws on the view that language can be regarded as a well-structured environment with an inherently sequential nature and supports the notion that dyslexia is associated with a sequential or serial-order learning impairment. It extends previous research by showing that not only initial HRL in a single session, but also longer-term learning (with more practice) is affected, although the long-term retention of what is eventually learned is unaffected in dyslexia. By assessing lexicalization of verbal sequences in people with dyslexia, we have shown how a serial-order learning impairment may result in language impairment. Our results support the SOLID view positing that dyslexia and its variety of related linguistic and nonlinguistic dysfunctions may be traced back, at least to some extent, to a difficulty with learning serial-order information.

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Table 1

Participant characteristics. Means per group with standard deviations between brackets.

Ns = not significant. Group differences were tested with a one-way ANOVA on $df(1,46)$ for Experiment 1 and $df(1,33)$ for Experiment 2. IQ = estimated total intelligence, EMT= Eén Minuut Test.

	<i>EXPERIMENT 1</i>		<i>EXPERIMENT 2</i>		
	<i>Control</i> (n = 23)	<i>Dyslexia</i> (n = 25)	<i>Control</i> (n = 18)	<i>Dyslexia</i> (n = 17)	Group difference
Age (years)	21.34 (1.52)	20.60 (1.44)	20.28 (1.02)	21.35 (2.80)	<i>ns</i>
IQ	109.00 (10.11)	106.92 (10.93)	108.18 (9.46)	106.48 (12.13)	<i>ns</i>
EMT (words/1 min.)	101.83 (10.44)	83.29 (18.92)	93.00 (9.43)	73.52 (10.53)	$p < .001$
Klepel (nonwords/1 min.)	65.56 (12.50)	44.71 (13.03)	96.11 (11.07)	62.24 (13.31)	$p < .001$

Table 2

CVCVCV syllable sequences and overlapping base-words.

CVCVCV sequence	Base-word	Transcription	English Translation
bi-ki-na	bikini	/bi'kini/	<i>Bikini</i>
fi-na-lo	finale	/fi'nalə/	<i>final</i>
fy-si-cu	fysica	/'fizika/	<i>physics</i>
ho-re-co	horeca	/'horeka/	<i>catering</i>
ka-ra-to	karate	/ka'ratə/	<i>karate</i>
la-va-bu	lavabo	/lava'bo/	<i>kitchen sink</i>
la-wi-na	lawine	/la'winə/	<i>avalanche</i>
li-bi-du	libido	/'libido/	<i>libido</i>
me-ri-tu	merite	/me'ritə/	<i>merit</i>
no-ma-di	nomade	/no'madə/	<i>nomad</i>
pa-ra-di	parade	/pa'radə/	<i>parade</i>
re-si-di	residu	/rezi'dy/	<i>residue</i>
sa-fa-ra	safari	/sa'fari/	<i>safari</i>
sa-la-du	salade	/sa'ladə/	<i>salad</i>
sa-la-mo	salami	/sɑ'lami/	<i>salami</i>
sa-ti-ra	satire	/sɑ'tirə/	<i>satire</i>
va-li-do	valide	/va'lidə/	<i>valid</i>
vi-si-ti	visite	/vi'zitə/	<i>visit</i>

Table 3

Top panel: Mean standardized gradient values for both groups as a function of experiment (experiment 1 vs. experiment 2) and sequence type (filler vs. Hebb). Lower panel: Number of Hebb repetitions, averaged over the two Hebb sequences, for both groups as a function of delay after Hebb learning (0h in Session 1 vs. 24h in Session 2 vs. one month in Session 3).

	<i>EXPERIMENT 1</i>		<i>EXPERIMENT 2</i>	
	<i>Control</i>	<i>Dyslexia</i>	<i>Control</i>	<i>Dyslexia</i>
<i>Gradient</i>				
filler	-0.04 (0.32)	0.03 (0.25)	0.03 (0.41)	0.16 (0.19)
Hebb	0.60 (0.22)	0.41 (0.30)	0.57 (0.23)	0.43 (0.26)
<i>Number Hebb Repetitions to criterion</i>				
Session 1	9.41 (5.21)	13.86 (5.70)	7.58 (5.91)	16.58 (6.29)
Session 2	3.70 (1.90)	9.30 (7.07)	/	/
Session 3	4.22 (3.18)	7.52 (6.09)	3.38 (2.93)	7.82 (6.88)

Table 4

Overview statistical tests Experiment 1. $Df(1,46)$ and $df(2,92)$; Group = control vs. dyslexic; Sequence type = filler vs. Hebb; Delay = 24h vs. one month; PC = Planned Comparisons; $^{\circ} p \leq .1$; $^* p \leq .05$; $^{**} p \leq .01$; $^{***} p \leq .001$.

<i>Hebb learning: ANOVA with gradients</i>	<i>F</i>	η_p^2
Group	1.00	.02
Sequence type	74.62 ^{***}	.62
Sequence type * Group	4.73 [*]	.09
<i>Hebb learning: PC with gradients</i>		
Sequence type in Controls	56.12 ^{***}	.55
Sequence type in Dyslexics	21.80 ^{***}	.32
<i>Hebb learning: ANOVA with number of repetitions</i>		
Group	11.52 ^{**}	.20
Session	47.67 ^{***}	.51
Session * Group	1.58	.03
<i>Hebb learning: PC with number of repetitions</i>		
Dyslexics vs. Controls in Session 1	7.91 ^{**}	.15
Dyslexics vs. Controls in Session 2	13.53 ^{***}	.23
Dyslexics vs. Controls in Session 3	5.41 [*]	.11
<i>Retention: ANOVA relative subtraction measure</i>		
Group	.50	.01
Delay	.70	.01
Delay * Group	.44	.01
<i>Retention: PC relative subtraction measure</i>		
Dyslexics vs. Controls for Delay 24h	.37	.01
Dyslexics vs. Controls for Delay 1month	.60	.01

Table 5

Overview statistical tests Experiment 2. $Df(1,34)$ and $df(2,68)$ / $df(1,33)$ and $df(2,66)$ for analysis that include Session 2; Group = control vs. dyslexic; Sequence type = filler vs.

Hebb; Hebb List= new vs. old; $^{\circ} p \leq .1$; $^* p \leq .05$; $^{**} p \leq .01$; $^{***} p \leq .001$.

<i>Hebb learning: ANOVA with gradients</i>		
	<i>F</i>	η_p^2
Group	.00	.00
Sequence type	50.52 ^{***}	.60
Sequence type * Group	5.52 [*]	.14
<i>Hebb learning: ANOVA with number of repetitions</i>		
Group	16.13 ^{***}	.33
Session	43.37 ^{***}	.57
Session * Group	5.39 [*]	.14
<i>Hebb learning: PC with number of repetitions</i>		
Dyslexics vs. Controls in Session 1	18.43 ^{***}	.36
Dyslexics vs. Controls in Session 2	6.27 [*]	.16
<i>Retention: ANOVA with initial performance new vs. old Hebb</i>		
Group	14.87 ^{**}	.31
Hebb List	3.27 [°]	.09
Group*Hebb List	1.33	.04
<i>Retention: ANOVA with difference in number of repetitions (new-old)</i>		
Group	0.15	.00

Table 6

Mean reaction times (RT; milliseconds) for base-words and control words as a function of delay after Hebb learning (0h and 1 month) for dyslexic participants and control participants. Standard deviations are in parentheses.

	<i>Control</i>		<i>Dyslexia</i>	
	0h	1month	0h	1month
<i>RT</i>				
Base	514 (173)	516 (158)	609 (197)	577 (122)
Control	503 (153)	473 (145)	609 (197)	565 (117)

Figure Captions

Figure 1. Visual depiction showing an example of a set of trials in the Hebb learning task. In this example the learned lexical competitors are ‘lavabo’, ‘finalo’ and ‘nomadi’. F= filler trial, H= Hebb trial.

Figure 2. Retention of the Hebb material. A) Mean proportion of correctly recalled Hebb items on the different points of time for dyslexic participants and controls. Error bars denote standard errors. Left panel: final Hebb trial Session 1 vs. first Hebb trial Session 2, right panel: final Hebb trial Session 2 vs. first Hebb trial Session 3. B) Same retention graphs when including only those participants who reached the learning criterion in Session 1.

Figure 3. The lexical competition effect (i.e., base-words minus control words) in Experiment 2 as a function of group and delay after Hebb learning. Error bars denote standard errors.